AC 2010-120: SYNTHESIS OF LOW-VOLTAGE THREE-PHASE POWER FOR USE IN LOW-COST MOTOR AND SYSTEMS EXPERIMENTS AT THE SOPHOMORE LEVEL

Thomas Schubert, University of San Diego

Thomas F. Schubert, Jr. received his B.S., M.S., and Ph.D. degrees in electrical engineering from the University of California, Irvine, Irvine CA in 1968, 1969, and 1972 respectively. He is currently a Professor of electrical Electrical engineering Engineering at the University of San Diego, San Diego, CA, and came there as a founding member of the engineering faculty in 1987. He previously served on the electrical engineering faculty at the University of Portland, Portland OR and Portland State University, Portland OR and on the engineering staff at Hughes Aircraft Company, Los Angeles, CA. Prof. Schubert is a member of IEEE and the American Society of Engineering Educators (ASEE) and is a registered professional engineer in Oregon. He currently serves as the faculty advisor for the Kappa Eta chapter of Eta Kappa Nu at the University of San Diego.

Ernest Kim, University of San Diego

Ernest M. Kim received his B.S.E.E. from the University of Hawaii at Manoa in Honolulu, Hawaii in 1977, an M.S.E.E. in 1980 and Ph.D. in Electrical Engineering in 1987 from New Mexico State University in Las Cruces, New Mexico. His dissertation was on precision near-field exit radiation measurements from optical fibers. He worked as an electrical engineer for the University of Hawaii at the Naval Ocean Systems Center, Hawaii Labs at Kaneohe Marine Corps Air Station after graduating with his B.S.E.E. Upon completing his M.S.E.E., he was an electrical engineer with the National Bureau of Standards in Boulder, Colorado designing hardware for precision fiber optic measurements. He then entered the commercial sector as a staff engineer with Burroughs Corporation in San Diego, California developing fiber optic LAN systems. He left Burroughs for Tacan/IPITEK Corporation as Manager of Electro-Optic Systems developing fiber optic CATV hardware and systems. In 1990 he joined the faculty of the University of San Diego. He remains an active consultant in radio frequency and analog circuit design, and teaches review coursed for the engineering Fundamentals Examination. Dr. Kim is a member of the IEEE, ASEE, and CSPE. He is a licensed professional electrical engineer in California.

Frank Jacobitz, University of San Diego

Frank G. Jacobitz was born in Göttingen, Germany in 1968. He received his Diploma in Physics Physics from the Georg-August Universität, Göttingen, Germany in 1993, as well as M.S. and Ph.D. degrees in mechanical engineering from the University of California, San Diego, La Jolla, CA in 1995 and 1998, respectively. At He has been at the University of San Diego, San Diego, CA since 2003, where he is currently a Professor of mechanical engineering. From 1998 to 2003, he was an Assistant Professor of mechanical engineering at the University of California, Riverside, Riverside, CA. He has also been a visitor with the Centre National de la Recherche Scientifique at the Université de Provence (Aix-Marseille I), France. His research interests include direct numerical simulations of turbulent flows with shear, rotation, and stratification, as well as bio-fluid mechanical problems at the micro-scale. Prof. Jacobitz is a member of the American Society of Mechanical Engineers (ASME), the American Association for the Advancement of Science (AAAS), the American Physical Society (APS), the American Geophysical Union (AGU), and the Deutsche Physikalische Gesellschaft (DPG). He currently serves as the faculty advisor to the student section of the ASME at the University of San Diego and on the council and executive committee of the Pacific Division of the AAAS.

Synthesis of Low-Voltage Three-Phase Power for Use in Low-Cost Motor and Systems Experiments at the Sophomore Level

Abstract

The electrical engineering program at the University of San Diego is currently revising its curricular treatment of electrical power and electrical machines at several levels and for students in all engineering majors. During the development of a three-phase system and synchronous motor laboratory experience for sophomore-level engineering students, budgetary and safety concerns led to the decision to work with three-phase systems at voltage levels less than 25V and power levels less than 5W. A three-phase 5V generator used in a commercially available low-cost "mini dynamo massager" served as the motor for this project.

The development of a three-phase low-voltage source became the primary challenge presented by the decision to work at low voltages. Since the study of three-phase systems was a significant portion of the exercise, PWM sources, appropriate if only motor characteristics were of interest, were judged to be inappropriate. The laboratory experience required a low-voltage replica of commercial three-phase power: sinusoids with 120° phase separation. The faculty design team was unable to find such a source commercially at low cost and designed, built, and tested several different sources. In addition to a transformer solution, two electronic circuits were implemented in the initial trials of the laboratory exercises: (a) digital synthesis using synchronized counters, D/A conversion, and wave shaping, and (b) digital synthesis using EPROMS and D/A conversion. Each of these three-phase synthesizers was developed with an estimated parts cost of less than US$10 (assuming appropriate DC power availability).

The design and implementation of the sources is described as well as the design and assessment of the three-phase system and synchronous motor laboratory experience in which they were used. Student learning was assessed through questionnaires at the beginning and end of the laboratory period. The questionnaires addressed both student knowledge and student confidence levels. The assessment showed a significant overall increase of both student knowledge and student confidence in the application of that knowledge. On a five-point scale, overall student-reported knowledge increased slightly more than one point and overall confidence increased by 1.33 points. Faculty assessment of knowledge, as measured by scoring short answers to knowledge questions, showed good correlation to the student-reported scores with the students reporting somewhat higher knowledge change than the faculty perceived.

The low-voltage electronic three-phase synthesizers allowed for a safe and meaningful three-phase system and synchronous motor laboratory experience for students who have minimal knowledge of the subject at low cost. While these three-phase sources were initially developed on a protoboard-based trainer, the team is continuing development of them as stand-alone devices. As such, these three-phase sources could provide a useful resource for many programs.

I. Introduction

The curricular treatment of electrical power and electrical machines is currently under revision at the University of San Diego (USD). Of particular interest in this study are the laboratories associated with two sophomore-level electrical engineering courses. One of the courses is a traditional one-semester, electrical engineering major circuits course with complex power and three-phase systems occupying, at most, a few lectures at the end of the course and having minimal coverage of electrical machines. For these students, the study of electrical power and machines is covered primarily in a later, upper-division course, *Principles of Electrical Power.* The second course, also of one-semester duration, is of more diverse content: it is designed as a broadly-based introduction to electrical engineering for mechanical engineering and industrial & systems engineering students (the other engineering majors at USD). In that second course, three-phase systems and electrical machines occupy approximately 20% of the course. Two years ago, a DC motor experiment using subfractional-horsepower motors was introduced into these courses as a first step in the USD curricular revisions. Assessment results of the study were published[1] and reviewers strongly suggested expanding the work to include AC motors.

The new challenge, described here, was to create a single three-phase system and synchronous motor laboratory exercise that could easily and simultaneously be performed by approximately twenty students in either of these two courses, working in groups of two or three, within a single three-hour laboratory period. The working budget was US$800 for ten identical work stations. Such a small budget immediately eliminated the possibility of purchasing a significant number of fractional-horsepower (~150W) motors and/or variable speed, three-phase drives.

While each station in the electrical engineering laboratories at USD is equipped with a single 208VAC (line voltage – 120 VAC phase voltage) three-phase outlet, these three-phase outlets have been historically unused for both safety concerns and the general lack of need. Since USD engineering students at the sophomore level have no experience working with voltages greater than ~30 V or power levels more than ~5W, and without time to teach and enforce appropriate safety practices, it was decided to develop a three-phase system with similarly low voltage and power levels. Previous success with subfractional-horsepower (<5W) DC motors[1] also led the team of USD engineering faculty to believe that such an effort would be fruitful.

Low-voltage three-phase sources generally are not commercially available, nor was it obvious where appropriate AC motors could be found. One of the USD faculty team members is engaged in consulting activities centered on environmentally "green" toys. In the course of that work, a "mini dynamo massager"[2] was dissected and discovered to have a three-phase five-volt generator. This generator fulfilled the basic requirements and was chosen as the initial motor for this project. Unable to find appropriate commercial three-phase sources at low cost, the team designed and built a variety of sources: these sources were used in the initial (spring 2009) offering of the laboratory experiences. Each of the designs, describe in detail in Section III, was realized at very low parts cost.

Note that the laboratory experience described here is focused on the basic understanding of balanced three-phase systems and synchronous motors. The setup is substantially simpler than those used in upper-division power electronics[3,4] or electrical machinery[5,6] labs. Due to its low cost, the laboratory experience and its associated laboratory equipment are well suited to small universities, community colleges, and any program with limited resources.

II. Experimental Goals

The basic project goals were:

- to develop a meaningful three-phase system and synchronous motor laboratory experience for (primarily) sophomore engineering students who have only introductory knowledge of the subject,
- to improve student knowledge concerning the basics of those systems,
- to give the students increased confidence in applying the knowledge obtained,
- to work at voltages and currents that are safe for lower-division students, and
- to develop a set of experiments, and associated laboratory equipment that could be easily scaled up to at least 10 identical lab stations at reasonable cost.

In order to meet those goals, the team:

- developed a set of experiments
- designed, tested and built three types of low-voltage three-phase sources
- designed and built a simple motor mount
- designed and built a small-scale dynamometer
- assessed student gains in knowledge and confidence due to the lab experiences

Each activity is described in the following sections of this paper.

III. Low-Voltage Three-Phase Source Development

The development of low-voltage three-phase sources became the primary challenge presented by the decision to work at low voltage and power. Since the study of three-phase systems was a significant portion of the exercise, PWM sources, appropriate if only motor characteristics were of interest, were judged to be inappropriate. The laboratory experience required a low-voltage replica of commercial three-phase power: sinusoids with 120° phase separation. The faculty design team was unable to find such a source commercially at low cost and designed, built, and tested several different sources.

Six different low-voltage three-phase source configurations were considered to accomplish project goals:

- Transformers in a Y-configuration (a three-transformer solution),
- Transformers in a Δ-configuration (a two-transformer solution),
- Analog synthesis using synchronized oscillators,
- Digital synthesis using synchronized counters, D/A conversion, and wave shaping,
- Digital synthesis using EPROMS and D/A conversion, and
- Digital synthesis using a microprocessor and D/A conversion.

Of these possibilities, three (transformers in a Δ, synthesis with synchronized counters, and synthesis with EPROMS) were used for the lab exercise during the spring 2009 semester.

The relatively high cost of a plug for the 208V outlet (>US$16 each) eliminated the transformers in a Y-configuration possibility for the initial trials. Accurate phase separation of synchronized analog oscillators required design efforts beyond the scope of this low-budget project, and that configuration was similarly eliminated. Three-phase digital synthesis using a microprocessor is being considered for future development. While the transformers in a Δ configuration was used in the initial trial, various limitations of that design, as discussed in Section VI.A, have eliminated that configuration from further development.

Of particular interest in this paper are the digital-synthesis sources. Digital synthesis eliminates the need for three-phase power input, allows for easy amplitude and frequency variation, and provides the possibility of a stand-alone low-voltage three-phase power source. Each digital-synthesis source was initially implemented using TTL (74LSXX) discrete components on a protoboard-based digital trainer (C.A.D.E.T or equivalent). The only functions that the trainer provided were DC power and a variable-frequency digital clock: functions that could easily be included in final implementations.

A. Synchronized-Counter Synthesis

One of the synthesized source configurations is based on three synchronized four-bit up/down counters. The basic plan for this configuration, as shown in the block diagram of Figure 1, was to:

- Create three appropriately phase-separated stepped-triangle waveforms,
- Wave shape each triangle waveform into a stepped-sinusoid, and
- Power amplify and low-pass filter each stepped sinusoid.

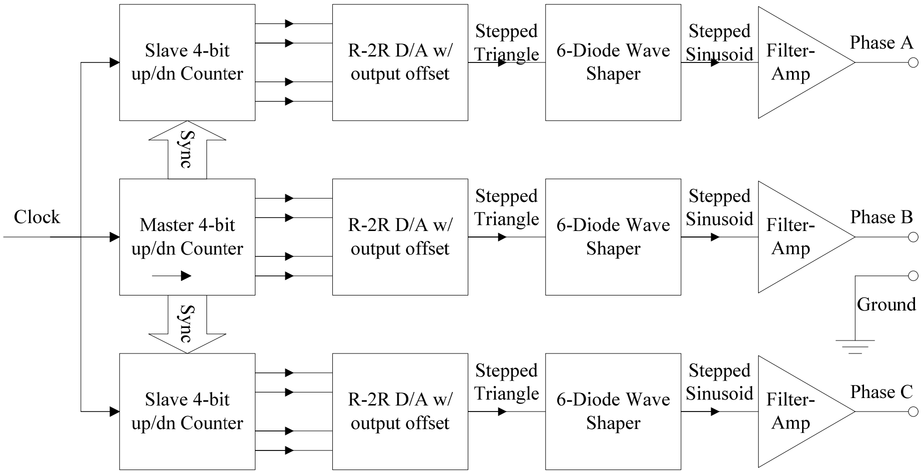

Figure 1 Block diagram for synchronized counter low-voltage three-phase source

Four-bit up/down counting was chosen for two basic reasons:

- there are thirty counts (a number divisible by three) in each cycle of a four-bit up/down count cycle (0–15–0): achieving 120º phase separation between phases could easily be achieved by successively delaying up/down count cycles by ten counts. While the divisible-by-three property is true for all even numbers of bits,
- the department had a large number of four-bit up/down counter chips (74LS193) in stock.

Each counter's digital up-down count cycle is converted into analog stepped-triangle waves using an R-2R ladder network[7] (the departmental stock did not include appropriate D/A chips) and level shifted at the summing amplifier of that network so that the resultant waveform is centered about zero volts. The triangle waveforms are then shaped into stepped sinusoids with a six-diode network[8]. The shaped outputs are finally smoothed (low-pass filtered) and power amplified to form the three separate phases. The motor chosen for the project required more current than in-stock op amps could provide, and a class B power amplifier, within the feedback loop of the amplification stage, was added to each phase. A circuit diagram of the prototype analog portion of each phase is shown in Figure 2.

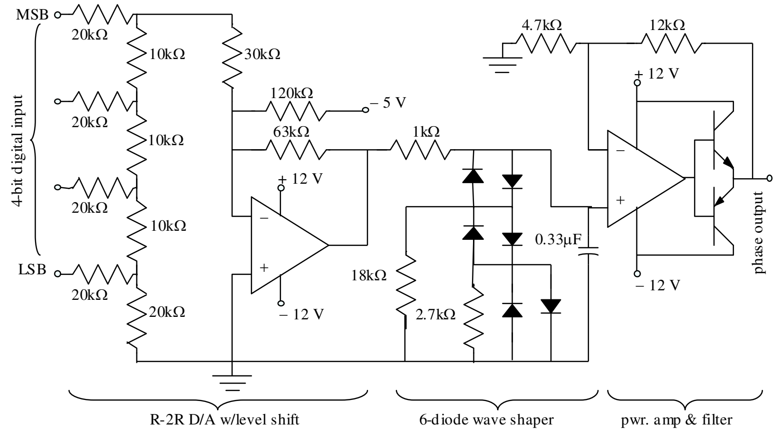

Figure 2 Circuit diagram of the analog portion of each counter-based phase

Four-bit digital synthesis, appropriately wave-shaped, provided good sinusoids with all harmonics more than 35 dB below the fundamental, 2-4% total harmonic distortion (each measured at 60Hz), and phase separation, as measured by student teams during the lab period, within 2° of ideal (Figure 3).

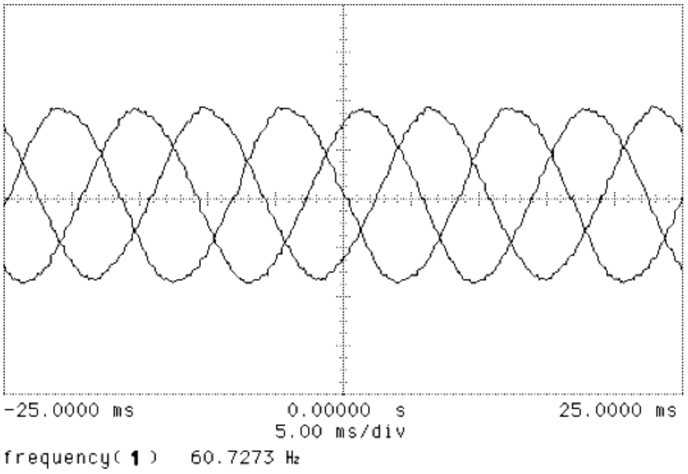

Figure 3 Four-bit counter-based synthesis of three-phase power

The prototype synchronized-counter, three-phase source, as realized on a digital trainer, is shown in Figure 4. Frequency variation for the three-phase synthesizers was accomplished by varying the trainer's function generator frequency, while amplitude variation for the initial trials was accomplished by replacing three identical resistors in the power amplifiers (one for each phase).

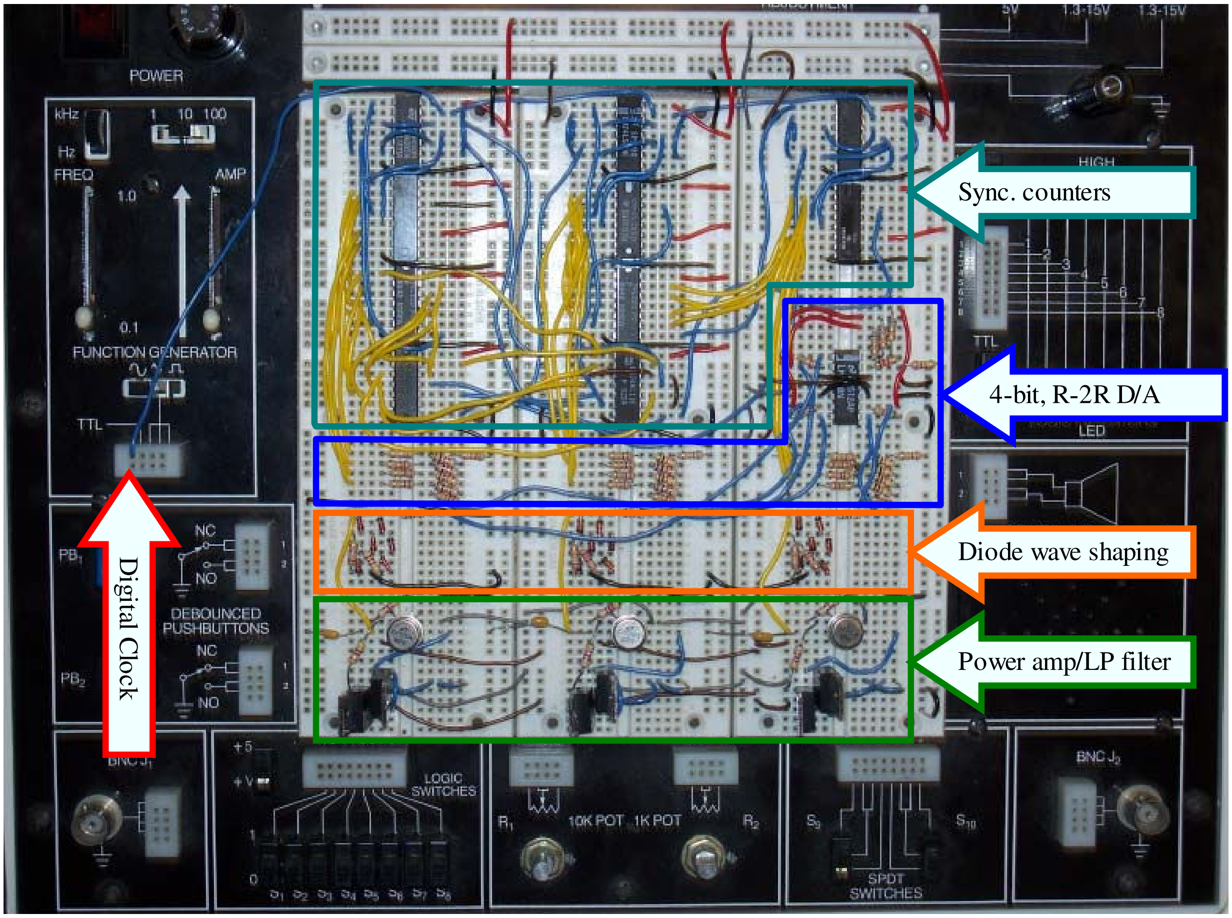

Figure 4 Prototype counter-based low-voltage three-phase synthesizer

Basic chip cost of the counter-based implementation is estimated (all components were in departmental stock) to be approximately US$10 per station. While this TTL-based source had low parts cost, assembly on protoboard-based digital trainers proved to be quite time intensive. Without any staff support, the investigators were able, due to time limitations, to implement only two counter-base sources for the initial trials.

In order to improve durability and utility, this source will be implemented as a stand-alone item, based on printed circuit boards, with 120VAC input, controllable output frequency, and variable output amplitude, early in 2010. The digital logic components will, most likely, be implemented on a FPGA, but the three counters will likely remain as separate chips. The laboratory exercises will then be again performed in May 2010 with multiple copies of this (and at least one other) standardized source. The performance of the second-generation sources will be assessed at that time. The investigation team will also disseminate, at the 2010 ASEE Annual Conference, the particulars of the standardized low-voltage three-phase sources upon finalization of the designs.

B. EPROM-Based Synthesis

Two eight-bit EPROMs were the basis for another synthesized source configuration. Driven by an eight-bit counter, fifteen of the EPROM output bits were formed into three five-bit stepped sinusoids and converted into analog signals using an R-2R ladder network as shown in the block diagram of Figure 5. The choice to use five-bit digital signals was based on the eight-bit output of the EPROMs available in the departmental stock:

- five bits per channels is the maximum for two eight-bit EPROMs,
- three EPROMs would logically provide eight-bits per channel, and
- no eight-bit D/A chips were in stock – an eight-bit R-2R ladder network D/A was considered too complicated for the initial prototypes.

The synthesized signals are then smoothed (low-pass filtered) and power amplified. As was the case for the other digital-synthesis source, a class B power amplifier, within the feedback loop of the amplification stage, is added to each phase to provide sufficient output current to drive the chosen motor.

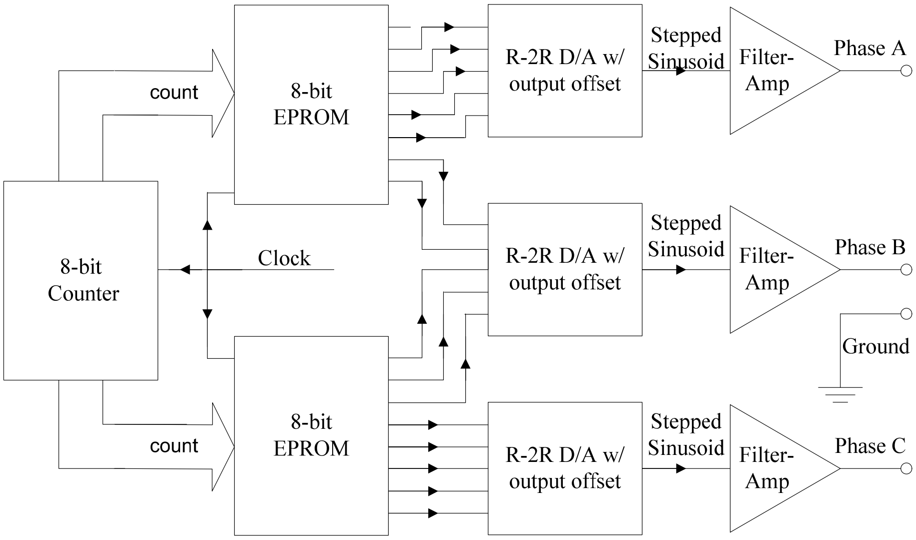

Figure 5 Block diagram for EPROM-based low-voltage three-phase source

Only one station of the EPROM-based configuration was used in the initial trials due to limited development time, resources, and support. The EPROM-based source was also constructed on a protoboard-based digital trainer (Figure 6). As was the case with the other digital-synthesis source, the only functions the trainer provided were DC power and a variable-frequency digital clock. EPROM-based digital synthesis, provided good sinusoids (Figure 7) with all harmonics at least 35 dB below the fundamental, as little as 2.5% total harmonic distortion (each measured at 60Hz), and phase separation within ~4° of ideal.

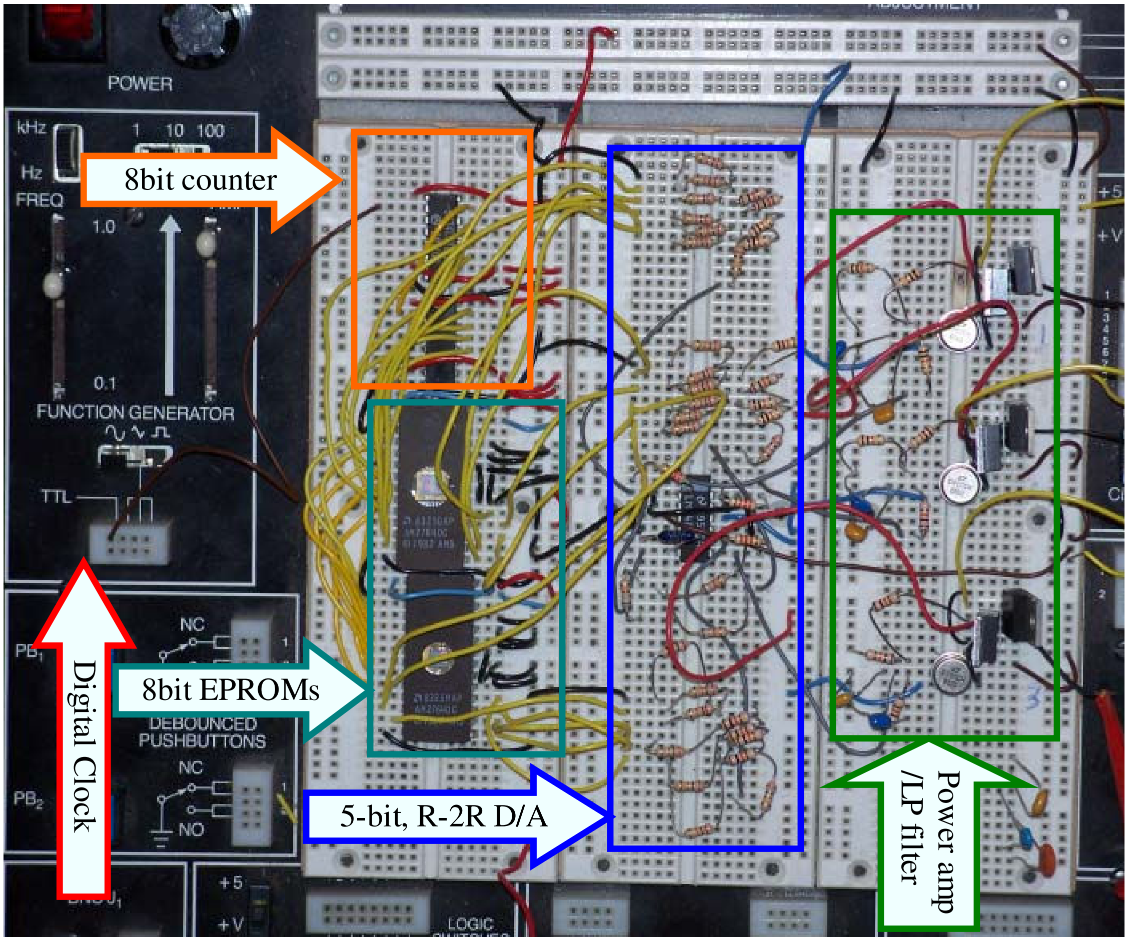

Figure 6 Prototype EPROM-based low-voltage three-phase synthesizer

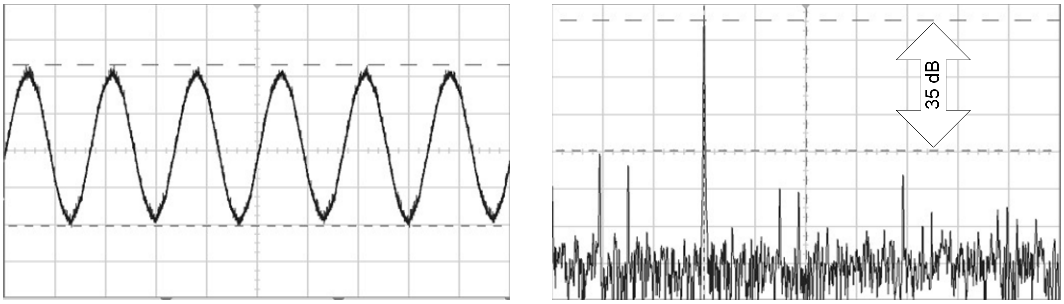

Figure 7 Five-bit EPROM-based synthesized power and its spectrum

The EPROMs used (D2764) were previously donated to the department. With the additional TTL and analog circuitry necessary, this station could be implemented on a trainer for a parts cost of approximately US$8 per station. Early in 2010, the team will implement a version of this source as a stand-alone item with 120VAC input, controllable output frequency, and variable output amplitude. While five-bit synthesis appears to be adequate for the purposes of the experiment, it is likely that the second-generation EPROM-based synthesizer will feature eight bits per channel synthesis (three EPROMS), D/A chips rather than an R-2R ladder, and a 255 (as opposed to the current 256) count cycle to improve proper phase separation. That version will also be tested in May 2010 and an assessment of its performance and the particulars of its final design will be disseminated at the 2010 ASEE Annual Conference.

IV. Three-Phase System and Motor Experiments

The experiments were designed to explore several basic concepts concerning balanced three-phase systems. Specifically, experimental evidence would be collected to verify that:

- Line and phase voltages and currents have specific magnitude and phase relationships,
- The phase relationships are dependent on the phase sequence,
- A simple equivalence exists between balanced Y-connected and balanced Δ-connected loads, and
- Each phase of a balanced, three-phase load dissipates the same complex power.

Evidence would also be collected to verify several basic concepts concerning synchronous motors:

- Motor speed is proportional to input electrical frequency,
- Motor speed is not dependent on input voltage or load (within reason),
- Motor rotational direction is dependent on the input electrical phase sequence ,
- Synchronous motors are energy conversion devices, and
- Motor torque is a complex function of input electrical quantities.

In order to make appropriate measurements for motor performance, three items need to be fabricated: a slotted disk (used, in conjunction with a transmissive optoswitch, to form a simple tachometer for motor speed measurements), a motor mount, and a small-scale dynamometer. The slotted disk was cut on the department's laser cutter and glued onto the motor's concentric, rotating housing. The motor mount was fabricated from a U-shaped piece of flat plastic, also cut on the laser cutter, and two DIP sockets, used for mechanical mounting of the motor assembly on the protoboard while serving no electrical function. This mount is shown in Figure 8 with the synchronous motor and the motor's original mount screwed in place. Care was taken with alignment so that the DIP sockets could be inserted into a typical electrical protoboard and the tachometer's slotted disk would operate without interference. The motor small-scale dynamometer was based on the spring scale – clothespin dynamometer used in a DC motor experiment at USD[1].

The experimental procedure was broken into four distinct segments: two of which (Y-connected loads and Δ-connected loads) dealt with basic balanced three-phase systems and two (unloaded motor operation and loaded motor operation) with synchronous motor characteristics. The procedural introduction, distributed with the experiment, included sections reviewing simple three-phase systems, balanced loads, Y-Δ equivalence, and synchronous motor basics.

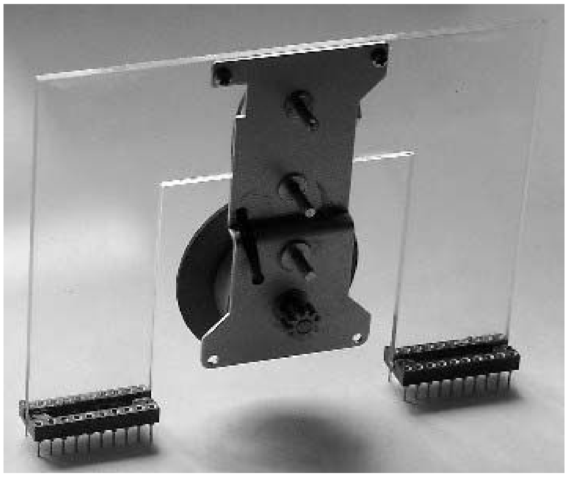

Figure 8 Fabricated synchronous motor mount

A. Three-Phase System Experiments

Students were directed to connect a balanced Y-load consisting of a 330Ω resistor and a 10μF capacitor in series for each phase and to operate at 60 Hz. The line and phase voltages and currents at the load were determined using both a multimeter and an oscilloscope. Magnitude and phase comparisons were made. Total complex power delivered to each phase of the load was computed. The phase sequence was determined then reversed so that comparisons could be made.

In order to study Δ-connected loads, students were asked to configure their source as a positive sequence source. Students determined the Δ-connected load equivalent (~3.3μF in series with ~1kΩ) to the previous balanced Y-connected load and connected it to their source. Again, line and phase voltages and currents were determined using appropriate lab equipment and the measurements compared to theory. The total complex power was computed and compared to that for the Y-load equivalent.

Y-connected load measurements proved to be accurate and repeatable. Phase-line voltage relationships ($\sqrt{3}$ in magnitude and 30° in phase) were easily demonstrated. All phases of the balanced load returned essentially identical values. The measurement capabilities of the oscilloscopes in the laboratories (subtraction of waveforms as well as built in measurement of amplitude and phase difference) proved invaluable. A summary of typical experimental data for the positive phase sequence only is shown in Table I. Negative phase sequence results were virtually identical aside from the phase reversals.

Table I Typical Y-connected load student data
(positive sequence data only)

Item	$\lvert\;\rvert$	ϕ	Item	$\lvert\;\rvert$	ϕ	Item	$\lvert\;\rvert$	ϕ
V_{an}	11.9 V_{p-p}	0°	V_{bn}	11.9 V_{p-p}	–120°	V_{cn}	11.9 V_{p-p}	122°
	4.03 V_{rms}	---		4.03 V_{rms}	---		4.09 V_{rms}	---
I_{an}	28 mA_{p-p}	69°	I_{bn}	28 mA_{p-p}	–50 °	I_{cn}	28 mA_{p-p}	–170°
	9.4 mA_{rms}	---		9.4 mA_{rms}	---		9.6 mA_{rms}	---
V_{ab}	20.6 V_{p-p}	39°	V_{bc}	20.4 V_{p-p}	–81°	V_{ca}	20.8 V_{p-p}	160°
	7.02 V_{rms}	---		7.03 V_{rms}	---		7.04 V_{rms}	---
S_{ab}	29–j25 mVA		S_{bc}	29–j24 mVA		S_{ca}	30–j25 mVA	

Δ-connected load measurements proved to be similarly accurate and repeatable. The use of "determine" rather than "measure" in the laboratory written procedure allowed students to explore different methods for obtaining values of line and phase currents: various teams used a variety of techniques. Again, all phases of the balanced load returned essentially identical values and the equivalence of the Y and Δ loads (both line current and complex power) was easily demonstrated. A summary of typical experimental data is shown in Table II.

Table II Typical Δ-connected load student data

Item	$\lvert\;\rvert$	ϕ	Item	$\lvert\;\rvert$	ϕ	Item	$\lvert\;\rvert$	ϕ
V_{ab}	20.6 V_{p-p}	0°	V_{bc}	20.4 V_{p-p}	–119°	V_{ca}	20.8 V_{p-p}	121°
	7.03 V_{rms}	---		7.02 V_{rms}	---		7.05 V_{rms}	---
I_{ab}	16 mA_{p-p}	69°	I_{bc}	16 mA_{p-p}	–50 °	I_{ca}	16 mA_{p-p}	–170°
	5.3 mA_{rms}	---		5.3 mA_{rms}	---		5.3 mA_{rms}	---
I_{Aa}	28 mA_{p-p}	39°	I_{Bb}	28 mA_{p-p}	–81°	I_{Cc}	28 mA_{p-p}	160°
	9.5 mA_{rms}	---		9.4 mA_{rms}	---		9.5 mA_{rms}	---
S_{ab}	30–j24 mVA		S_{bc}	30–j24 mVA		S_{ca}	30–j24 mVA	

B. Synchronous Motor Experiments

The initial unloaded motor exercises were more of observational nature than quantitative. Students were directed to connect the three-phase motor to their source (with a small-value resistor in series with each lead) and observed the motor's rotation. The students then interchanged any two motor leads, thereby reversing the phase sequence, and noted any changes in the motor performance (the motor reverses). Students constructed a simple tachometer using a slotted disk attached to the motor shaft and a transmissive optoswitch as a detector[1] as shown in Figure 9. Motor speed was measured and compared to the frequency of the input three-phase power. The number of motor poles, N_P, was determined by noting that the rotational speed of the motor (in RPM) is related to the frequency of the input electrical power, f_{EL}, by:

$$spd_{\mathrm{RPM}} = \frac{f_{\mathrm{EL}}\left(120\right)}{N_P}$$

Students were reminded that magnetic field poles come in pairs.

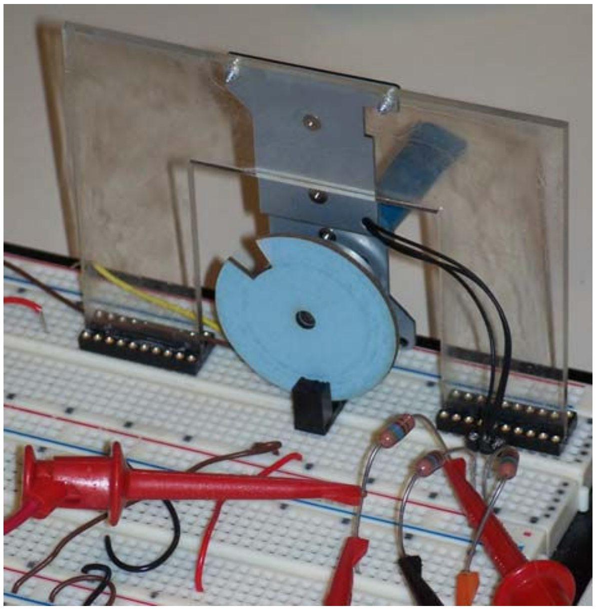

Figure 9 Motor speed measurement

If the students were using a variable-frequency source (in 2009 some stations used transformers in a Δ as the three-phase source and were therefore unable to alter the electrical frequency), they were asked to change the frequency of input power source and note that the motor rotational speed varies directly with frequency. All students were directed to vary the input voltage magnitude and note any change in rotational speed (no change occurs). The motor was then lightly loaded (with a finger against the shaft) and noted to have no change in rotational speed. With the motor again unloaded, the motor input voltage and current (and phase difference) were measured and motor input complex power was computed.

Loaded motor measurements were obtained by attaching the motor to a small-scale dynamometer (shown in Figure 10 using a digital jewelry scale to measure force). Output power was computed as the product of rotational speed and torque. Rotational speed was measured using the transmissive optoswitch tachometer of previous sections. Torque was computed as the product of the length of a lever arm (a clothespin with the spring removed and replaced by a screw) and the force. Force was measured using either a linear spring scale or a digital jewelry scale: student teams were given the option of choosing either. Since there was a gear on the output shaft of the motor, it was necessary to fabricate a smooth surface on which the lever arm could ride. A short segment of plastic tubing was slipped over the gear and a ballpoint pen top inserted into the other end of the tubing to form that surface.

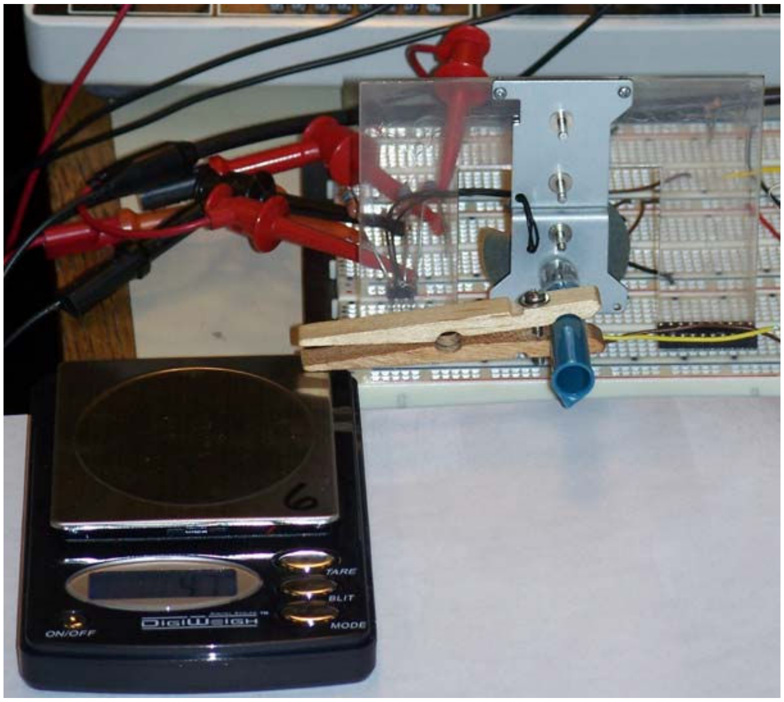

Figure 10 Synchronous motor output power measurement

This output power measurement was compared to input electrical power, determined from input voltage, current, and the phase difference. The efficiency of energy conversion was computed. By adjusting the tension of the clothespin on the rotating shaft, the load was altered and new power measurements and efficiency calculations performed and compared to previous values. The students were then asked to comment on the major electrical contributors to motor output mechanical power.

Students easily performed the unloaded motor operation exercises. The transmissive optoswitch circuitry for speed detection had been used in a DC motor experiment the previous week and was typically rebuilt by the student teams without difficulty. Programs wishing to diminish the time demands on the students may want to provide a protoboard with this circuitry prebuilt, thereby saving 10-15 minutes of lab time. Pole determination and motor reversal were performed by all students without any difficulty. Input line current and phase were determined from the voltage across the small resistor placed in line with each motor lead. Most students made measurements on only one phase and concluded the other phases performed identically. Typical unloaded motor data is shown in Table III.

Table III Typical unloaded synchronous motor data

f	spd	N_p	V_m	V_r	I	ϕ	S_{total}
60.2	602	12	2.65 V_{rms}	1.99 V_{rms}	0.355A_{rms}	24°	2.58+j1.15 VA
100.3	1000	12	2.94 V_{rms}	1.83 V_{rms}	0.327A_{rms}	30°	2.49+j1.44 VA

Loaded motor operation exercises also produced good, repeatable data (Table IV) with the exception that the phase angle between the input voltage and current was a somewhat noisy measurement. Students made best estimates of all values. While at first glance the efficiency of energy conversion looks quite bad for this motor, most of the conversion inefficiency can be attributed to the significant power required to run the motor unloaded.

Table IV Typical loaded motor data

spd	F	P_{mech}	V	I	ϕ	P_{el}	η
600RPM	0g	0	2.65 V_{rms}	0.355 A_{rms}	24°	2.58W	—
600RPM	0.5	19.6mW	2.67 V_{rms}	0.352 A_{rms}	23°	2.60W	0.75%
600RPM	1.3g	58.7mW	2.69 V_{rms}	0.348 A_{rms}	21°	2.62W	2.2%
600RPM	3g	117mW	2.7 V_{rms}	0.343 A_{rms}	17°	2.66W	4.4%
600RPM	4g	156mW	2.7 V_{rms}	0.339 A_{rms}	14°	2.67W	5.9%

While it had been hoped that motor cogging could be quantitatively evaluated, the prototype experimental apparatus was not up to the task. When the motor was sufficiently loaded so that cogging could be observed, the motor ran at irregular speed and appropriate speed measurements were not obtainable. It is hoped that improvements the load adjustment mechanism and the concentricity of the load bearing surface will improve cogging observations in the future.

V. Assessment of Student Learning

The aim of this study was to assess student learning in laboratory concerning three-phase systems and electric motors. Specifically:

- Does this lab activity increase basic understanding of the operation and modeling of three-phase systems and synchronous motors?
- Does student confidence in applying the concepts learned increase?

Short questionnaires were designed to provide insight into the student level of knowledge of three-phase systems and synchronous motors and their confidence in applying that material. At the beginning of the lab period, students were asked to score (on a scale from 1 to 5) their prior knowledge. Students were also asked to respond with a short answer to the knowledge questions. To provide further insight into actual student knowledge level, these short answers were later scored by the investigators. After the lab period, the questionnaires were again completed by the students and the post-exercise written responses scored by the investigators to measure changes in knowledge level. In order to track individual student incremental changes, the two questionnaires were stapled together, thereby preserving student confidentiality without the need for secret identification marks on the questionnaires. A total of forty-five surveys, split essentially equally between the two courses, were completed by the students. In cases where students did not complete all sections of the questionnaires, partial results were included in the study as appropriate: incremental score changes were computed only in those cases where students responded both before and after the exercise. The use of student-assigned scores to assess gains in student knowledge and confidence has been successfully used by the investigator team in previous studies[1,9].

A. Assessment of Student Knowledge

Eight questions concerning knowledge of the design process were asked before and after the lab exercise. The knowledge score was based on the following scale:

1 = No clue, this concept is new to me
2 = Low, I have only heard about the concept
3 = Moderate, I knew the concept but have not applied it
4 = High, I know the concept and have tried it
5 = Superb, I know the concept and have successfully applied it

The distribution of students' answers on their knowledge of the lab material before and after the experiment is given in Table V for each statement on the questionnaire. A histogram of the aggregate students' knowledge before and after the experiment is shown in Figure 11

Table V Knowledge of the subject matter survey statements with student responses pre-experiment and post-experiment with tabulated incremental changes.

Knowledge Statements student responses	When	Distribution					Incremental Change								
		1	2	3	4	5	-4	-3	-2	-1	0	1	2	3	4
What is three-phase AC?	pre	6	10	9	5	1					7	14	7	1	
	post		2	11	10	6									
What is a balanced three-phase load?	pre	6	10	13	3					1	5	15	8		
	post	1	5	9	11	4									
What is the difference between a Y-connected load and its equivalent Δ-connected load?	pre	1	11	12	5	2				3	4	13	4	5	
	post	1	1	7	10	10									
What electrical quantity determines the speed of a synchronous motor?	pre	13	10	6	2					1	5	11	11	1	
	post	1	4	17	7	1									
What electrical quantity is related to motor torque?	pre	10	12	8	1						7	10	11	1	
	post	2	2	16	6	4									
How can the motor average electrical power be measured ? What quantities need to be measured?	pre	12	9	9	1						9	14	4	1	
	post	3	8	10	6	2									
How is the output mechanical power of a motor measured? What quantities need to be measured?	pre	9	9	9	3					1	8	13	3	1	
	post	3	6	12	4	5									
What are the basic components of an optoswitch?	pre	18	3	5	4					2	8	10	3	3	
	post	6	4	5	9	3									

Students reported slightly greater initial knowledge of three-phase systems (mean = 2.58) as compared to synchronous motors (mean = 2.02), but reported similar, significant changes in mean scores due to the lab exercise (+1.06 and +1.09 change, respectively). The mean knowledge level increased for each question at or above 0.90 with the questions relating to motor speed and torque experiencing the greatest mean difference (+1.25 and +1.28 respectively).

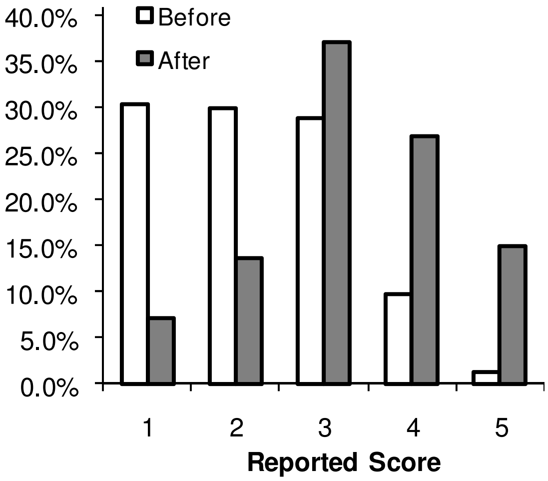

Figure 11 Overall student reported knowledge scores

Faculty scoring of the student short responses to the initial knowledge statements showed good correlation with student reporting of knowledge. Three-phase systems had a mean score of 2.42, while the mean score for synchronous motors was 2.00. Faculty scored a somewhat smaller, but still significant, overall mean knowledge increase of 0.57 with the questions relating to Y-Δ equivalence, three-phase systems, and motor speed experiencing the greatest mean difference (+0.79, +0.73, and +0.72 respectively).

The summary of the individual student incremental change in knowledge scores is also shown in Table V. On individual knowledge questions, students reported positive increments in 72.9% of their responses. Most students reported a positive knowledge increment of one (44.3%): smaller fractions indicated no change (23.6%) or a positive increments of two (22.7%%). Overall, a positive increment of three and a negative increment of one were reported as 5.8% and 3.6% of the responses, respectively.

Faculty scoring of the short written statements (Table VI) indicated knowledge increments similar to student reported increments. Within those pairings, faculty noted no change in 52.8%, a positive increment in 41.4%, and a negative increment in only 5.8% of the cases. The overall an average increment was +0.56. A histogram of the overall individual knowledge increments is shown in Figure 12.

Table VI Faculty scoring of student responses to knowledge questions pre-experiment and post-experiment with tabulated incremental changes.

Knowledge Statements faculty scoring	When	Distribution					Incremental Change								
		1	2	3	4	5	-4	-3	-2	-1	0	1	2	3	4
What is three-phase AC?	pre	12	23	23	8	4					29	17	5	1	
	post	1	10	28	17	4									
What is a balanced three-phase load?	pre	22	20	11	9	4					24	17	7	2	2
	post	6	12	23	11	8									
What is the difference between a Y-connected load and its equivalent Δ-connected load?	pre	15	31	14	5	7				2	31	14	7	6	
	post	5	21	20	11	13									
What electrical quantity determines the speed of a synchronous motor?	pre	33	14	3	1	5	2		2	4	26	7	2	3	
	post	24	17	6	7	8									
What electrical quantity is related to motor torque?	pre	27	25	10						3	30	16	3	2	
	post	15	25	18	4										
How can the motor average electrical power be measured ? What quantities need to be measured?	pre	21	15	8	6					2	21	9	2		
	post	11	17	16	8										
How is the output mechanical power of a motor measured? What quantities need to be measured?	pre	17	19	5	3	12		2		4	21	10	3	3	
	post	8	14	13	5	12									
What are the basic components of an optoswitch?	pre	24	14	6	8	4				2	27	7	5	5	
	post	9	16	7	14	6									

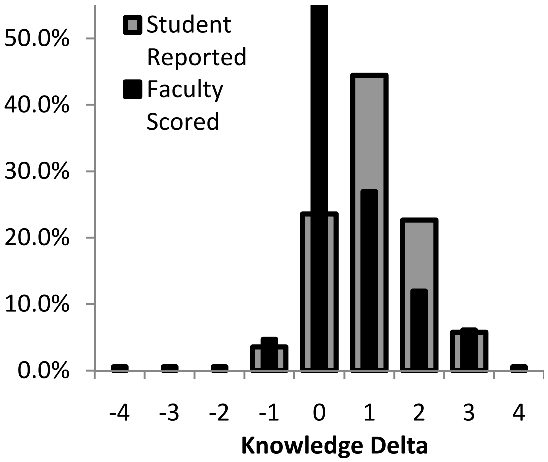

Figure 12 Histogram of Overall Knowledge Increments

B. Assessment of Student Confidence in Applying Concepts

Another portion of the questionnaire was designed to assess student confidence in applying the concepts of the design process. Eight questions were asked before and after the exercise was performed in order to assess student confidence and scored on same five-point scale as knowledge.

The distribution of student responses on their confidence in applying the concepts of the course material is given in Table VII for each statement on the questionnaire. A histogram with the students' aggregate confidence in applying the concepts of the course material is shown in Figure

13. Interestingly, students reported higher initial confidence in topics relating to synchronous motors (mean = 2.53) than three-phase systems (mean = 2.41): a reversal in comparison to reported initial knowledge. Each of these two general categories experience a significant overall average confidence gain: +1.29 for three-phase systems and +1.25 for synchronous motors. Students further reported increases in mean confidence scores greater than +0.75 on every question with knowing how to reverse a synchronous motor experiencing the greatest mean change of (+2.38).

Table VII Confidence in applying the concepts statements with student responses pre-experiment and post-experiment with tabulated incremental changes.

Confidence Statements student responses	When	Distribution					Incremental Change								
		1	2	3	4	5	-4	-3	-2	-1	0	1	2	3	4
I can determine electrical power in a three-phase system	pre	7	19	15	3						9	18	8	2	1
	post		4	16	11	4									
I understand the difference between line and phase voltages and currents	pre	8	13	17	4	1				1	5	19	9	4	
	post		3	7	20	6									
I know how to determine the Y-equivalent of a balanced Δ-connected load	pre	8	18	11	6	1				2	6	11	13	6	
	post		2	9	19	5									
I know at least one way to measure motor speed without touching the motor	pre	6	11	10	12	3			1	1	11	14	7	3	1
	post		3	10	14	2									
I can measure the output power of an electric motor	pre	8	13	14	5	3			2	3	6	17	9	1	
	post		6	15	14	2									
I can change the speed of a synchronous motor	pre	11	13	7	10	1			1	7	5	13	8	4	
	post		6	13	12	4									
I know how to reverse a three-phase motor	pre	20	11	8	3	2					2	6	11	9	10
	post		2	2	10	20									
I can properly connect an optoswitch and use it to detect motion	pre	17	7	8	9	1					7	11	11	7	2
	post		4	5	15	11									

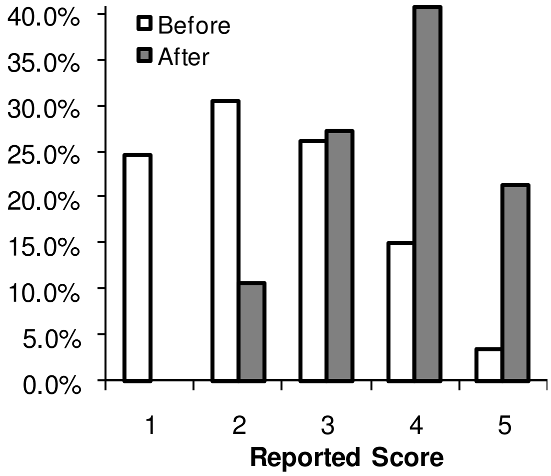

Figure 13 Overall Student Confidence Scores

A summary of the individual student incremental change in confidence scores is also shown in Table VII. On individual confidence questions, students reported positive increments in 77.3%

of their responses. Most students reported a positive increment of one (35.9%), followed by two (25.0%), three (11.8%), and four (4.6%). No incremental change was reported in 16.7% of the responses and negative increments were reported in only 5.9% of the responses. A histogram of the overall individual confidence increments is shown in Figure 14.

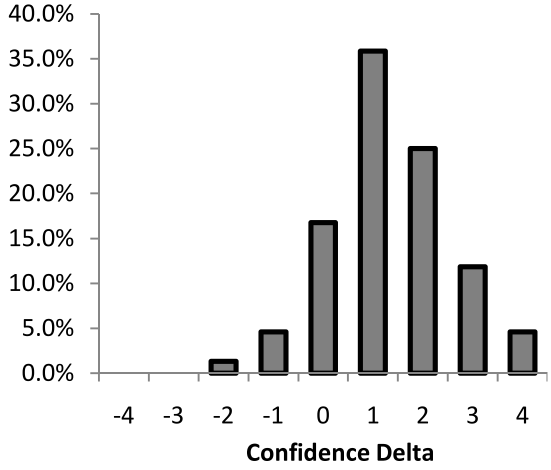

Figure 14 Overall Student Confidence Increments

VI. EXPERIMENTAL OBSERVATIONS AND PLANS FOR IMPROVEMENT IN EXPERIMENTAL TECHNIQUE

The decision to use low-voltage, low-power systems was judged to be correct. Due to student errors in various circuit interconnections (mostly placing ground in multiple locations), a few insignificant parts were slightly overheated as some devices began operating close to their rated values. However, no appreciable harm was done to any of the equipment and all students experienced a safe laboratory experience. Similar interconnection errors would have led to disastrous results if higher voltage/power systems had been in use.

A. Three-phase sources

The mixture of Δ-connected and Y-connected sources provided valuable insight into what the ideal source should be for this type of experiment. Many students at this introductory level appear to have trouble with the measurement/computation of complex power in the case a Δ-connected source and a Δ-connected load (the chosen motor was Δ-connected): the lack of a fixed ground terminal seemed to be the primary source of confusion. The team concluded that the ideal source for this type of laboratory experience should have the following characteristics:

- Identical output phases separated by ~120°
- Y-connected
- Variable in frequency over a range of at least one decade centered about 60Hz
- Variable in output voltage over a range of at least a factor of two centered at ~5Vrms
- Power output of ~2W/channel

Both digital synthesis sources performed well. Frequency variation was easily accomplished in each case by varying the digital clock rate and the motor responded well to input frequencies as high as 300Hz. Amplitude variation in this initial trial was accomplished for both digital synthesis cases by replacing three identical resistors in the circuits – unfortunately, most students were unwilling to perform that task just to see that nothing changed. The next generation of digital sources will have improved amplitude variation capability.

Transformer-based low-voltage sources have the inherent inability to vary frequency: thus, synchronous motor speed variation cannot easily be accomplished with this category of source. However, many available transformers have multiple taps on the secondary windings allowing easy output amplitude variation, albeit of limited variability. In order to provide a Y-connected source, three transformers must be used and a three-phase power connection must be available in the laboratory. The investigation team is moving away from transformer-based sources and is not planning to use them in spring 2010.

Initial parts cost of the three-phase sources was significantly lower than originally expected. Since the department had previously packaged 12.6/6.3V filament transformers individually for use in other laboratory courses, the two transformers in a Δ source implementation came at no cost to the project. Basic chip cost of the counter-based implementation is estimated (the components were all in departmental stock) to be approximately US$10 per station. Similarly, the EPROMs used in the other digital source implementation were old stock previously donated to the department – with the additional TTL and analog circuitry necessary, this station could be implemented on a trainer for a parts cost of approximately US$8 per station.

While the TTL-based sources had low parts cost, assembly of these sources on protoboard-based digital trainers proved to be quite time intensive (each contained as many as ten digital chips, seven op amps, etc.). Without staff support, the investigators were unable, due to time limitations, to implement more of these sources for the initial trials. Both of the sources described in Section III will be implemented on printed circuit boards, with 120VAC input, controllable frequency, and variable amplitude early in 2010. The laboratory exercise will then be performed with multiple copies of these standardized sources in May 2010, and the investigation team will disseminate the particulars of its standardized low-voltage three-phase sources at the 2010 ASEE Annual Conference.

B. Other experimental apparatus

The only other item directly purchased for this project was the motor. As was previously stated, these motors were imbedded as the generators in a hand-crank mini dynamo massager[2] which can be purchased for approximately US$16. While this motor was satisfactory for most experimental objectives, it suffers from low efficiency of energy conversion: the team continues to search for a better motor. Spring scales of appropriate capacity (10g) can typically be purchased for approximately US$8 each and, while equally accurate, are significantly less expensive than digital jewelry scales. Assuming typical electrical engineering lab stations, the total parts cost for implementing such an experiment is estimated to be under US$40 per station.

VII. Summary

The development of a meaningful three-phase system and synchronous motor laboratory experience met all its goals. The department was able to limit its purchases for this experiment to the three-phase motors (US$16 each): all other items were standard parts in stock. Even if all items needed for this experiment were to be purchased, it is estimated that an equivalent experiment could be accomplished for a per-station cost of less than US$40 (assuming that typical laboratory equipment and a protoboard-based digital trainer is available). Digital synthesis of low-voltage, three-phase AC did, however, require a considerable time commitment both for design and implementation.

Three separate types of low-voltage, three-phase AC sources were designed, implemented, and used in the exercise. Each produced accurate three-phase power with appropriately equal magnitude phases and correct phase separation with low distortion.

Data collection for the three-phase system portion of the laboratory experience went extremely well with all measurements within a few percent of theory. Data collection, analysis, and verification on subfractional-horsepower synchronous motors exceeded the expectations of the authors. The data collected was reliable, accurate, and repeatable. At no time did the motor power exceed 3W. Efficiency of energy conversion for these particular motors was low and the investigation team will continue searching for a better low-voltage, low-power synchronous motor.

An assessment of student learning showed a significant increase in both student knowledge and student confidence in the application of that knowledge. On a five-point scale, overall student reported knowledge increased slightly more than one point: overall confidence increased somewhat more (1.33 points). Assessment of knowledge by faculty compared to student report showed a good correlation with the students reporting somewhat higher knowledge change than the faculty reported.

Acknowledgement

USD Institutional Review Board approval was obtained for the Spring 2009 semester (Project Number 2009-05-114).

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